Trajectory Reconstruction for the Genesis Entry

Prasun Desai

Garry Qualls

Mark Schoenenberger

NASA Langley Research Center

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Genesis Mission Background

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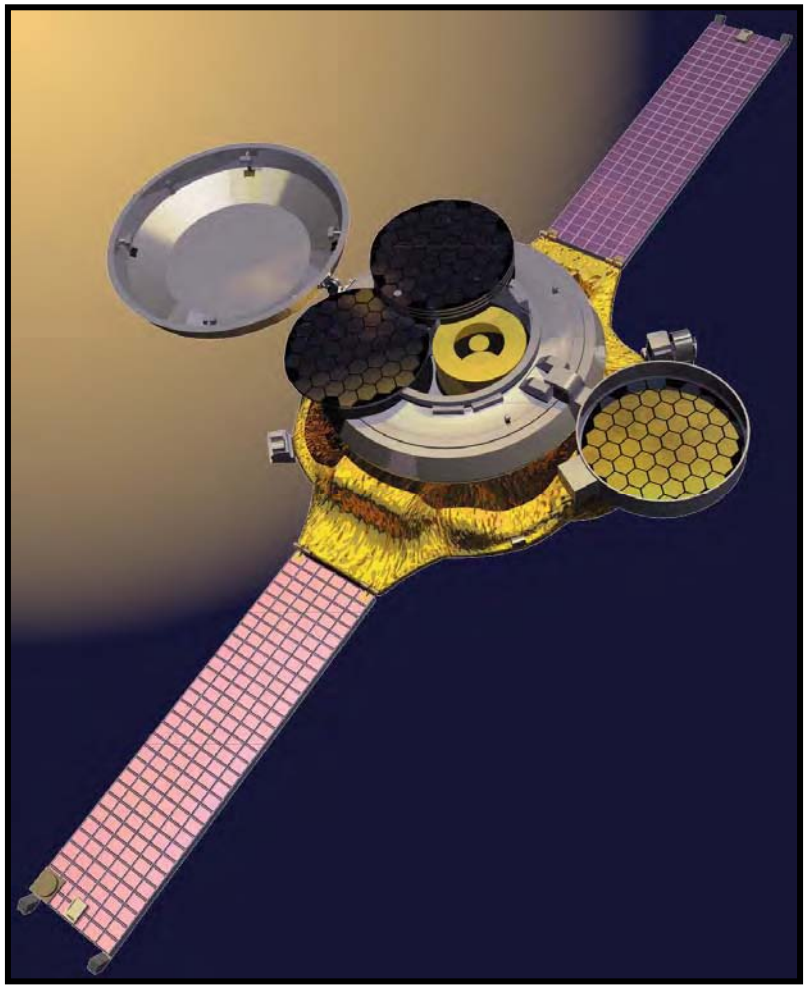
- Fifth Discovery mission
  - Launched on August 8, 2001
  - Inserted in to a halo orbit about the sun-Earth libration point (L1)
  - Collected solar wind particles for ~29 months
  - First mission to return samples from beyond the Earth-moon system



- Maneuver and targeting procedures placed capsule on desired entry flight-path on morning of September 8, 2004 at 15:52:47 UTC

Genesis Entry Live!

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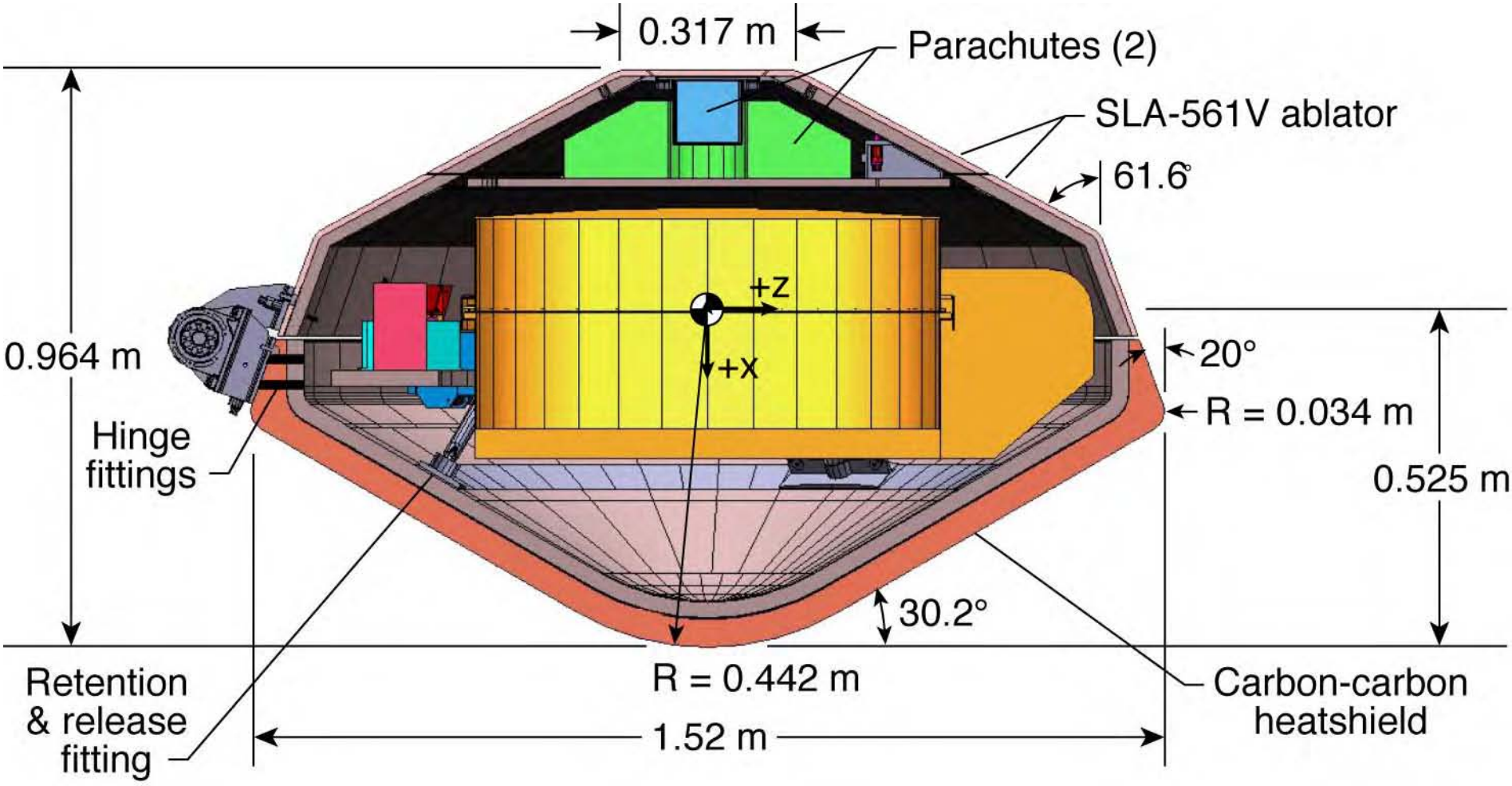
Capsule mass = 205.6 kg



Genesis Entry Live!

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QuickTime™ and a
decompressor
are needed to see this picture.

Genesis Nominal Entry Sequence

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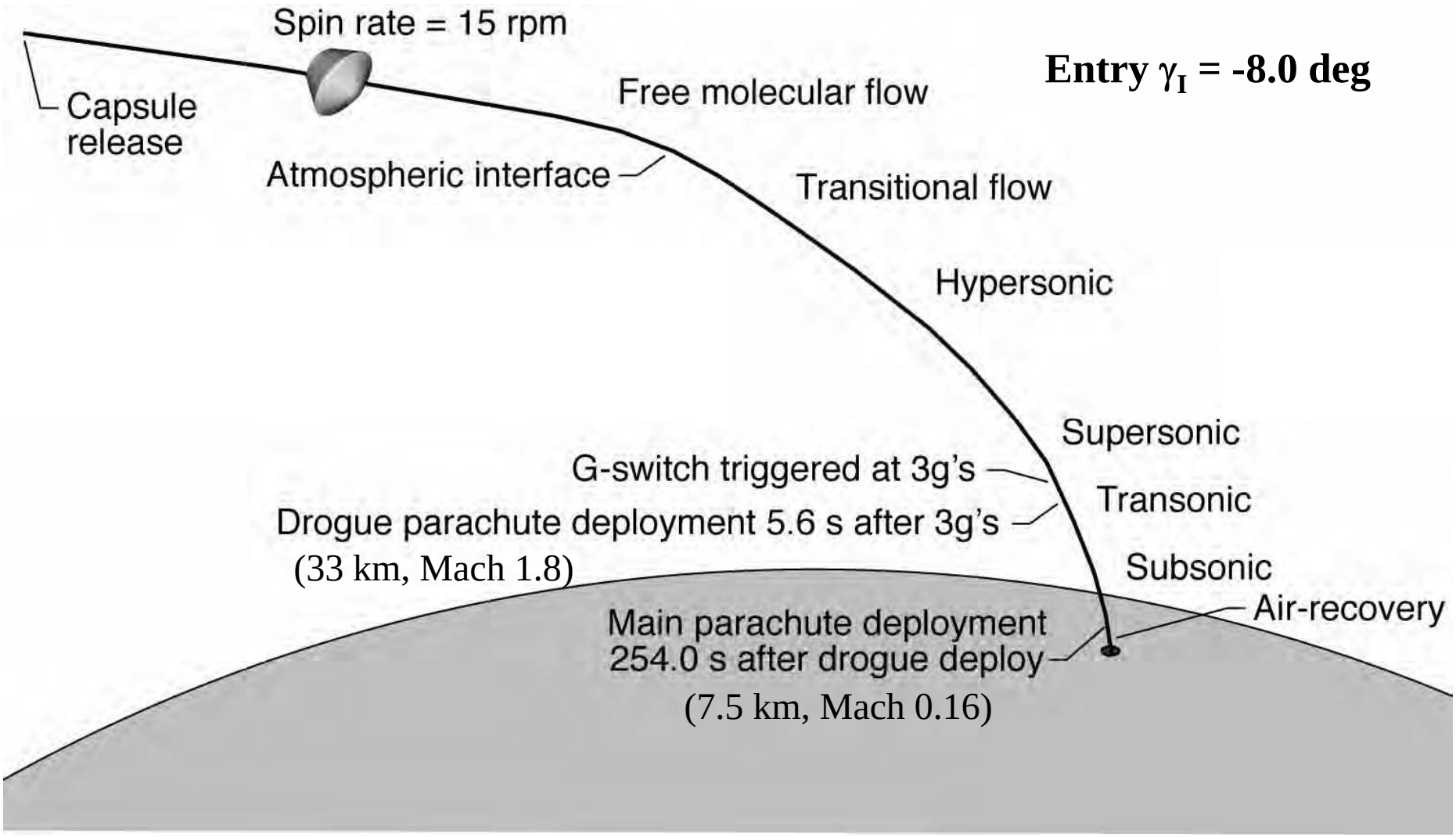
Entry V_I = 11.04 km/s

Entry γ_I = -8.0 deg



Genesis Impact Location

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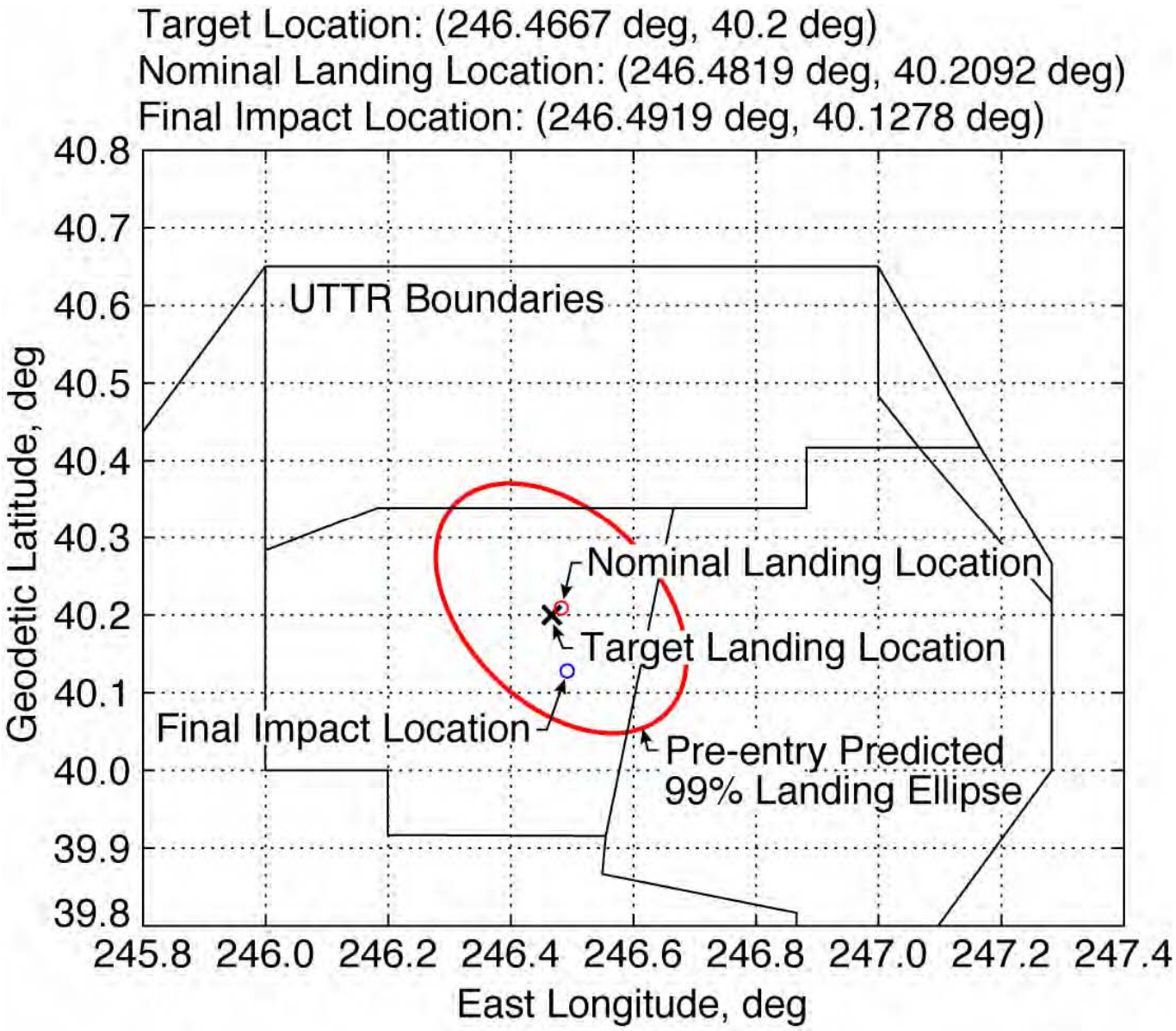


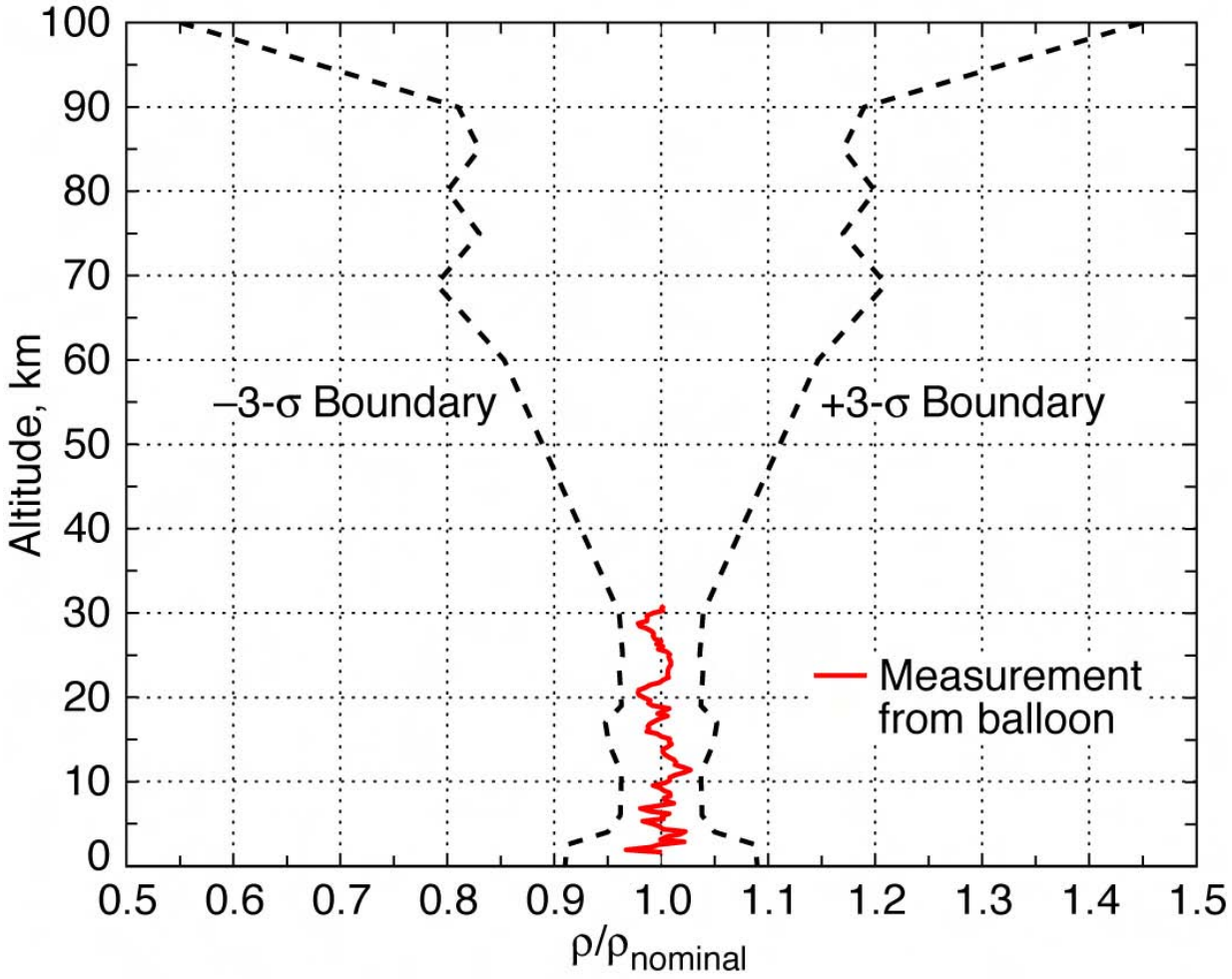
Genesis Reconstruction Effort

- Genesis capsule landed very close to the desired target
  - Understanding hypersonic flight performance is of great interest
  - Specifically, assessing how the pre-entry predictions of flight dynamics, aerodynamics, and aerothermodynamics
  - Identify Mach number for onset of capsule tumble

- Only limited data exists to perform reconstruction
  - No onboard sensors on capsule
  - Only available data source is from UTTR radar tracking stations
    - Video and tracking data
  - Balloon measurement of atmospheric properties up to 34 km four hours prior to entry

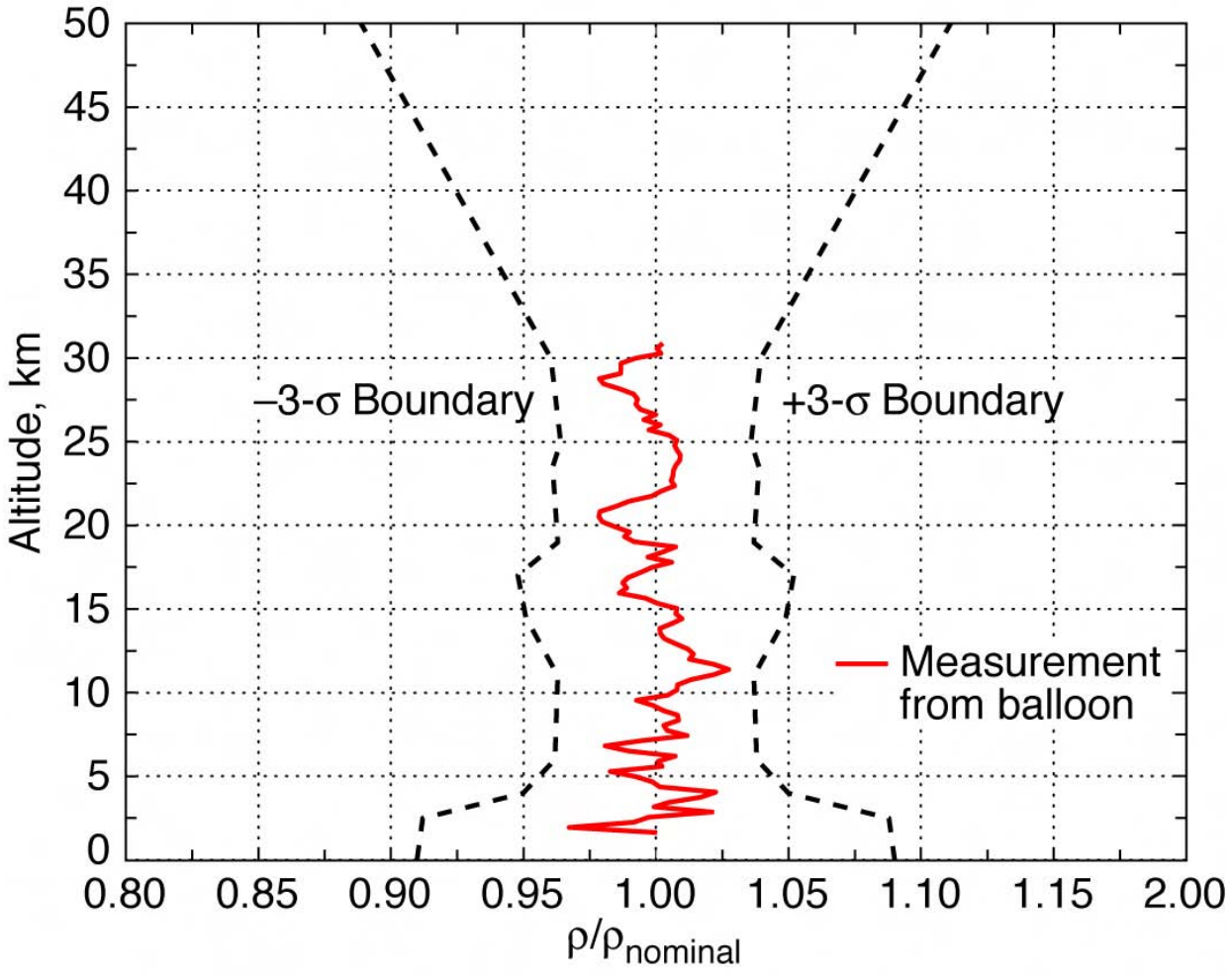
Density Comparison to GRAM Model

- Global Reference Atmosphere Model (GRAM) used for pre-entry prediction



Density Comparison to GRAM Model (cont'd)

- Variation of ±2.5% observed on entry day
- Corresponds to ~1.5-σ profile from GRAM variations



Wind Comparison to GRAM Model

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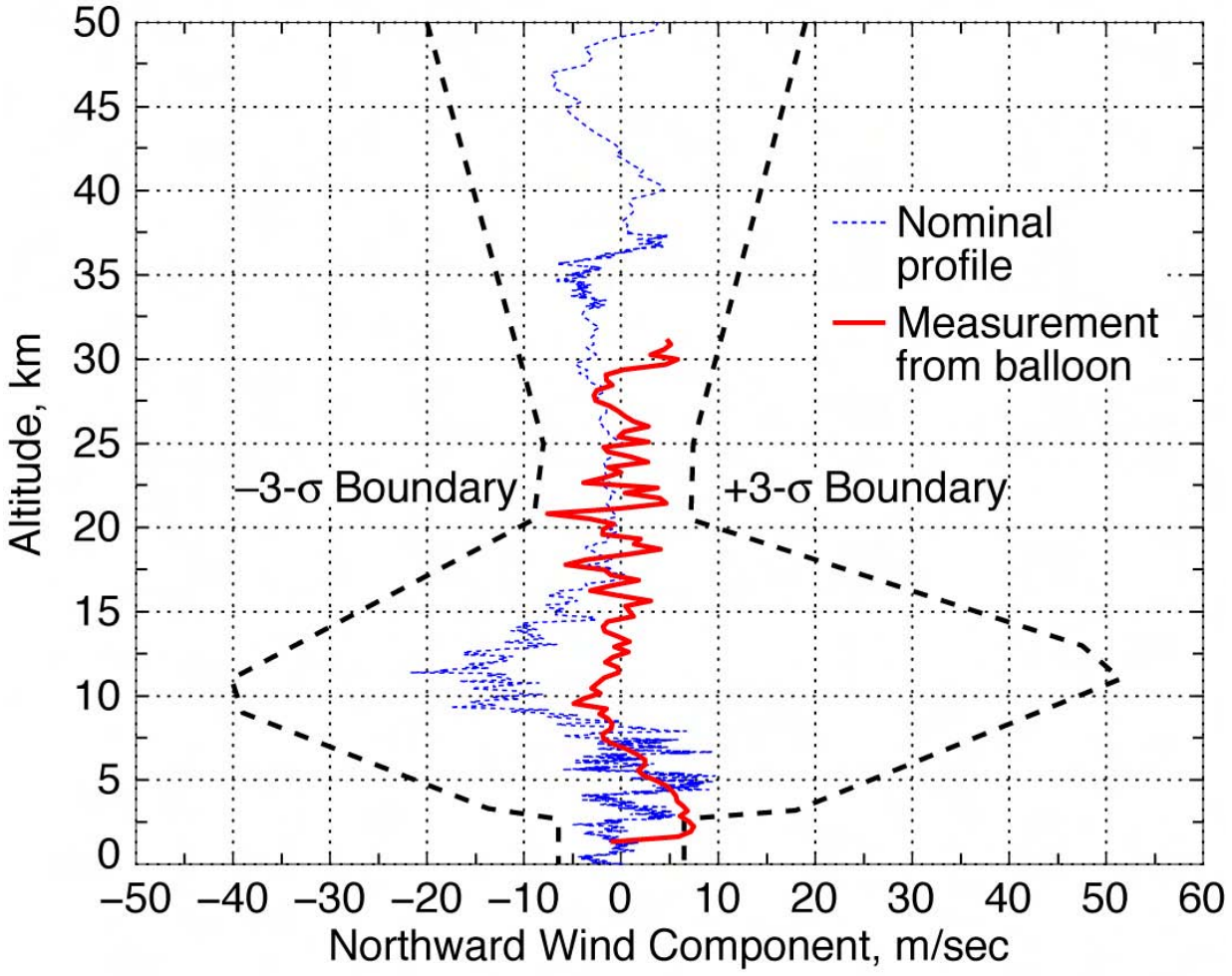
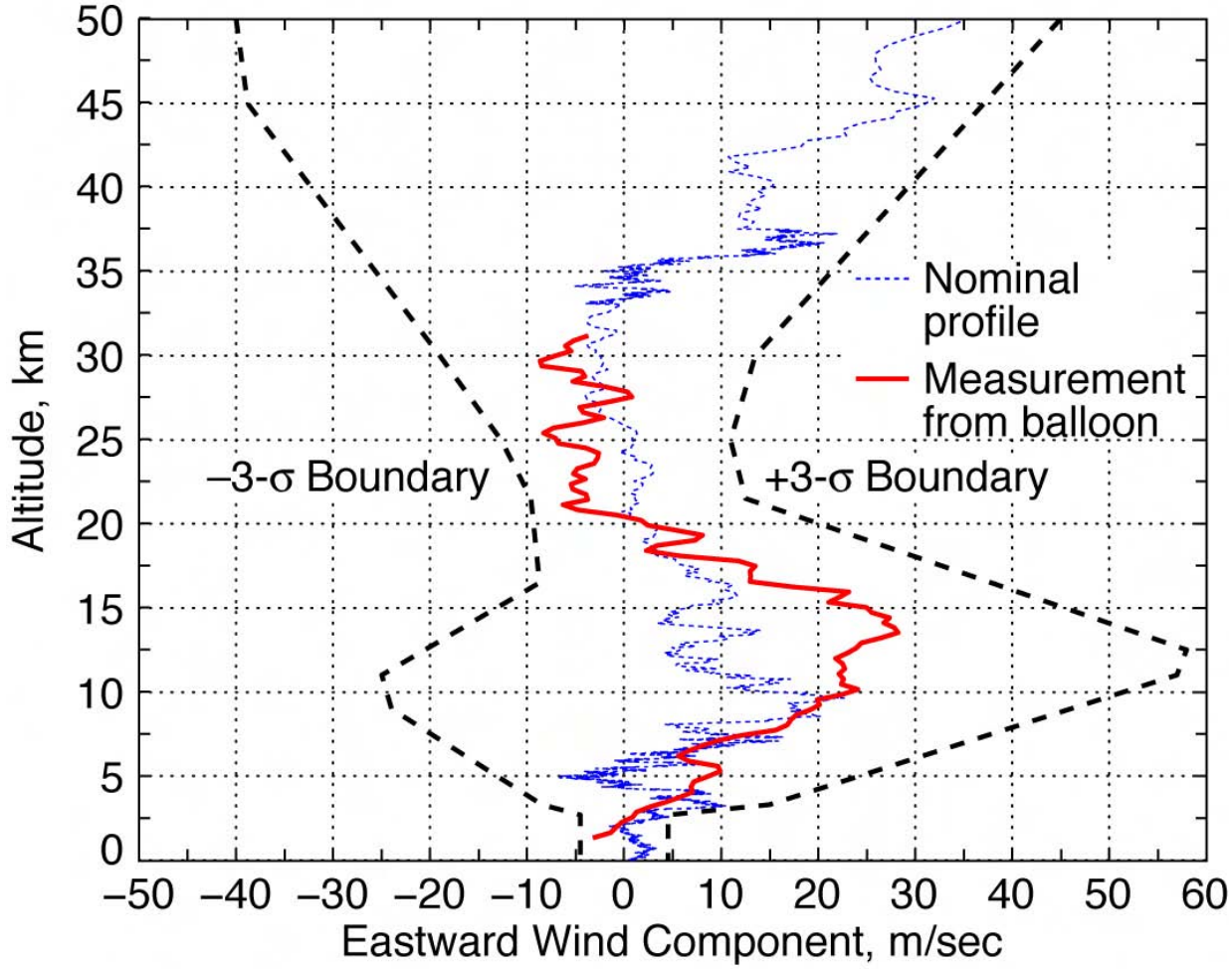
- Variation of ±5 m/sec observed on entry day



Wind Comparison to GRAM Model (cont'd)

- Sustained wind to the East observed (~27 m/sec at 12 km)
- Corresponds to ~1.5-σ profile from GRAM variations



Capsule Luminance from Infrared Video

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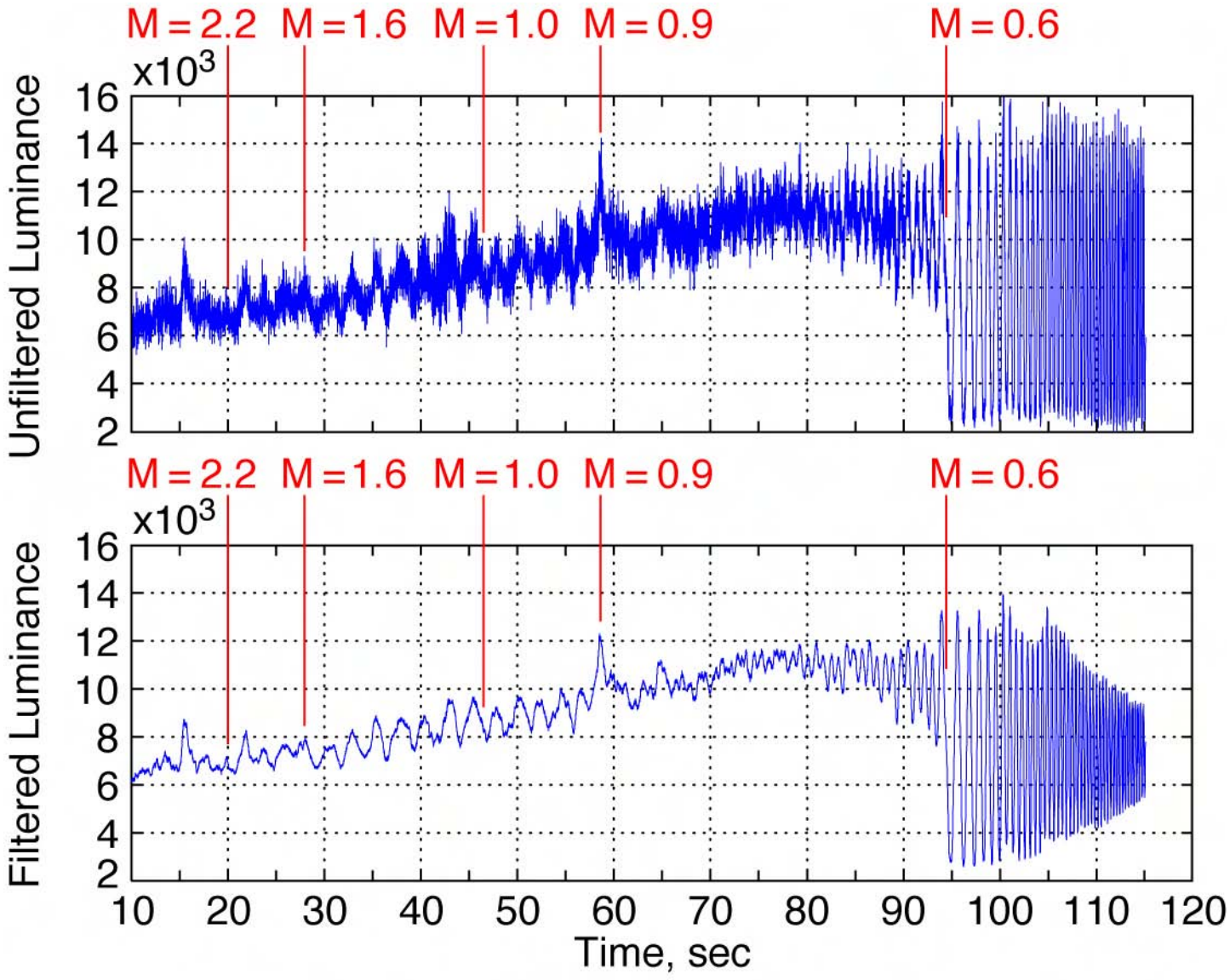

Frequency Contours of Luminance Data

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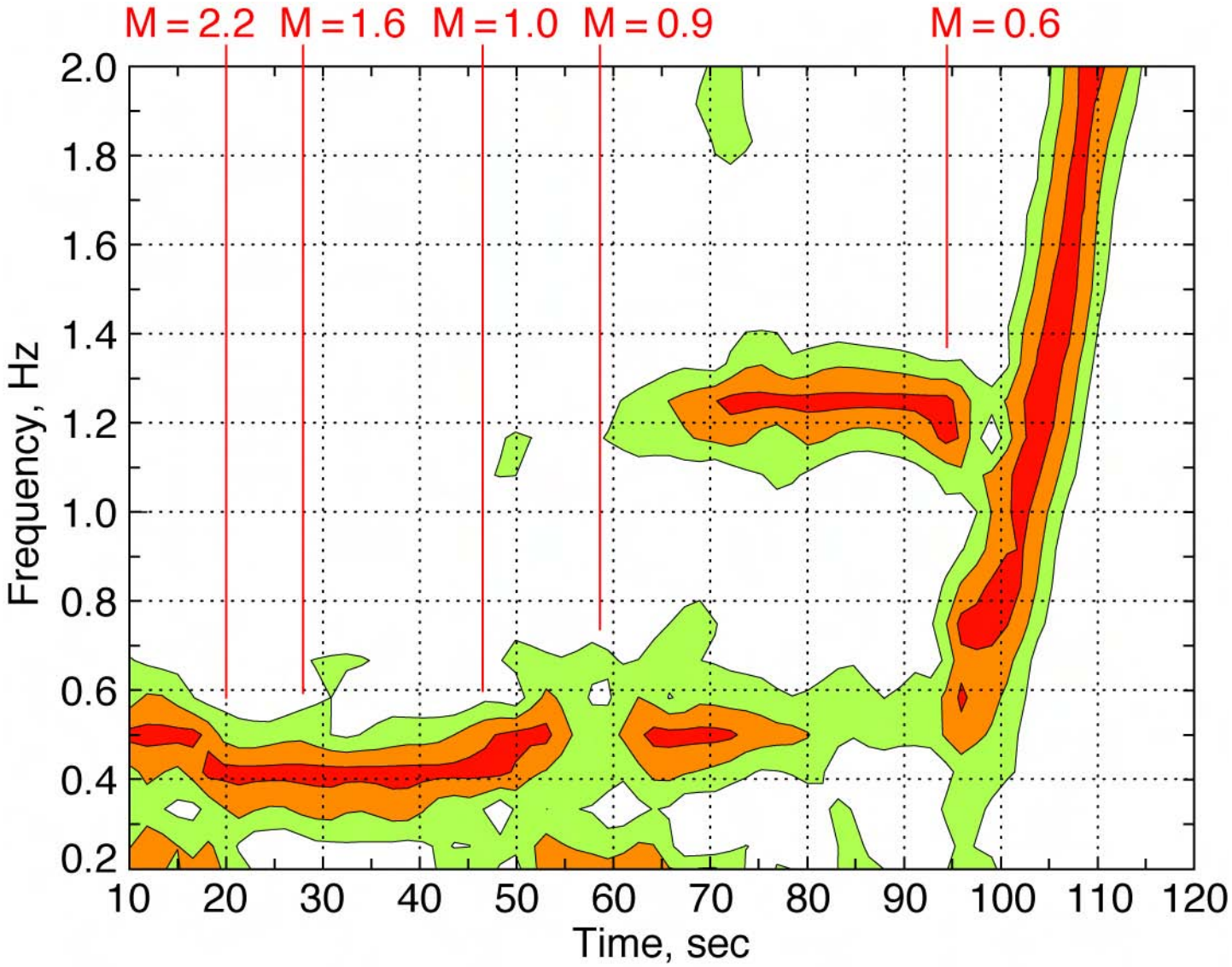
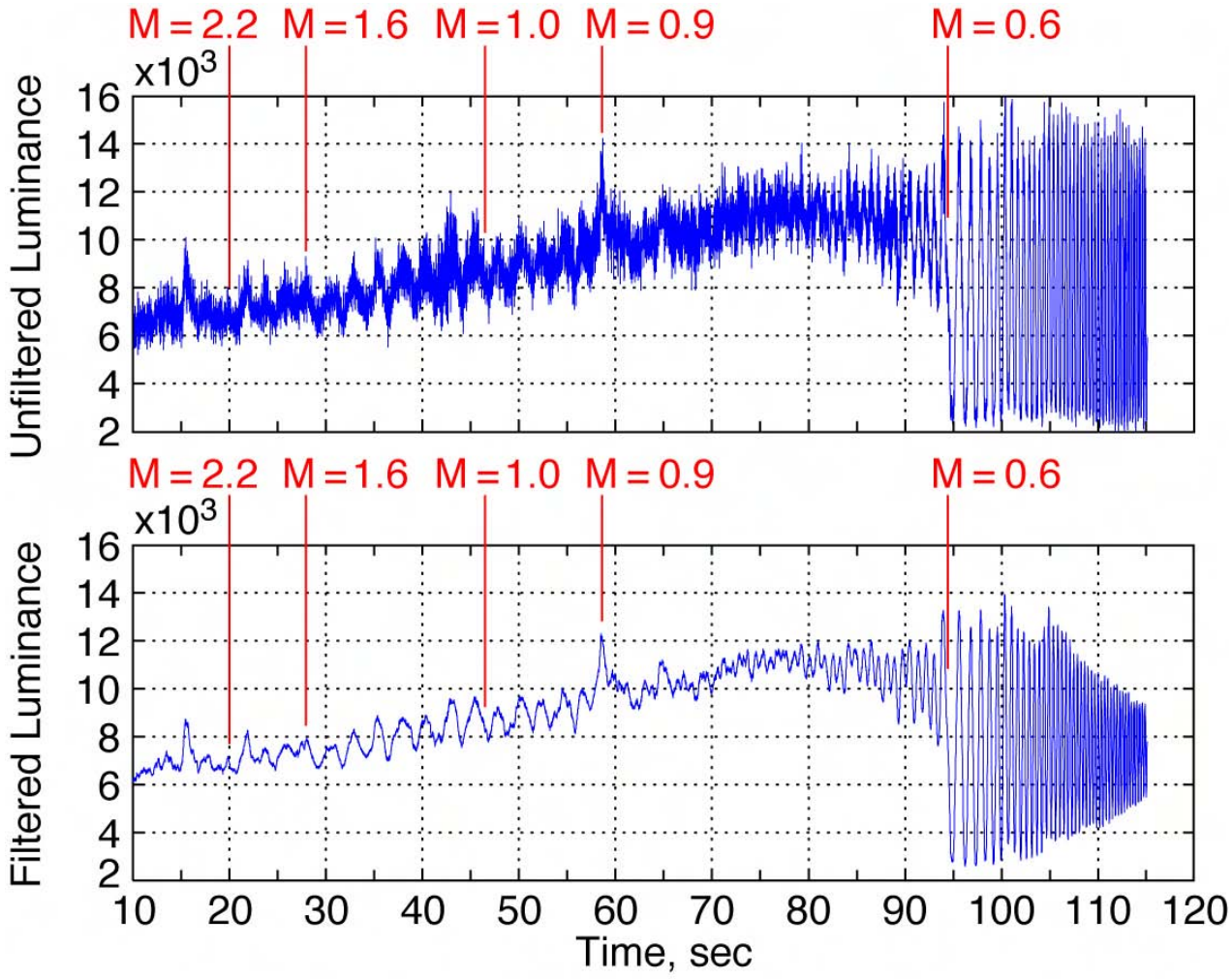


Capsule Luminance from Infrared Video

- Onset of tumble at Mach 0.9



Pre-Entry Simulation Capsule Attitude Prediction

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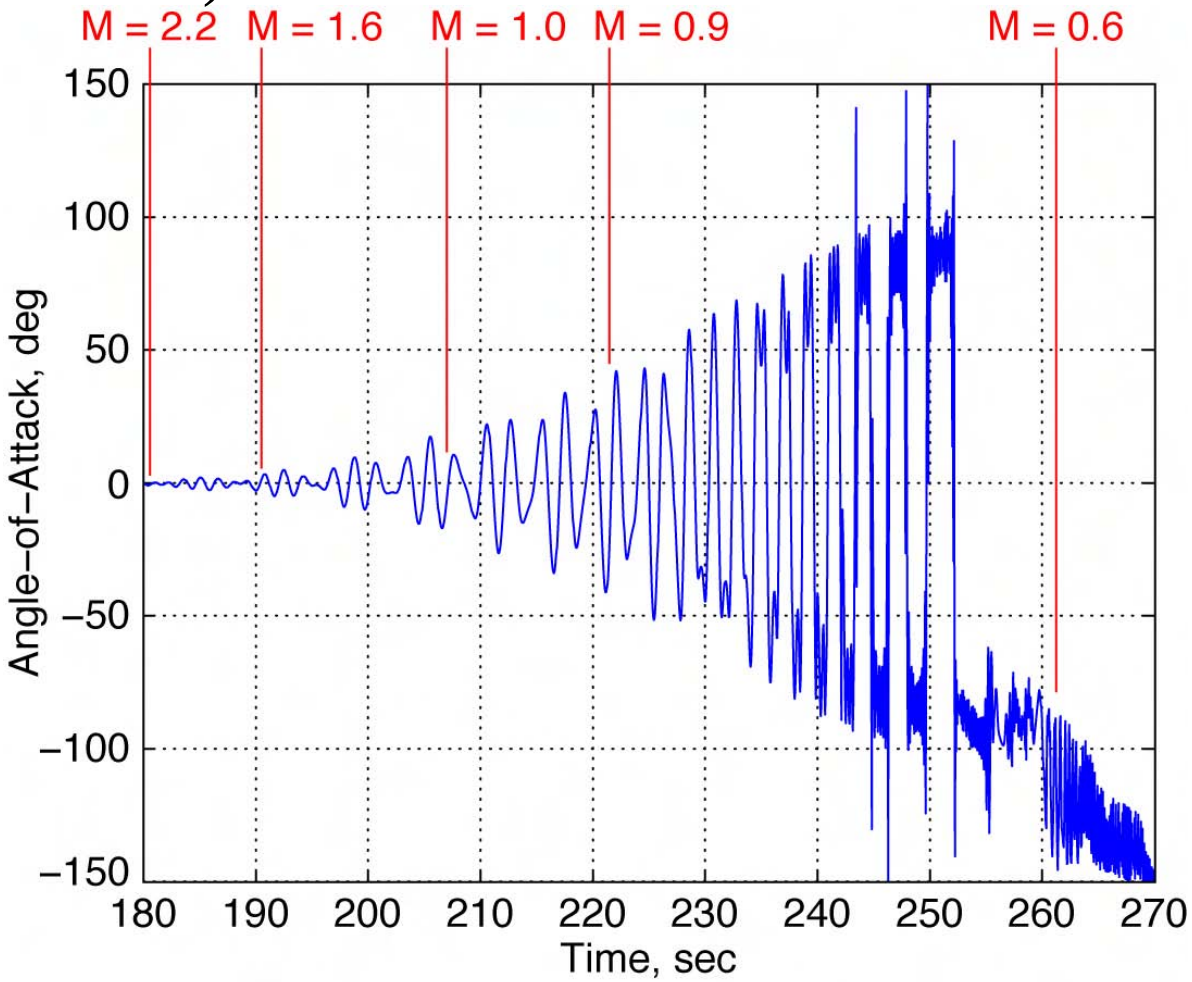
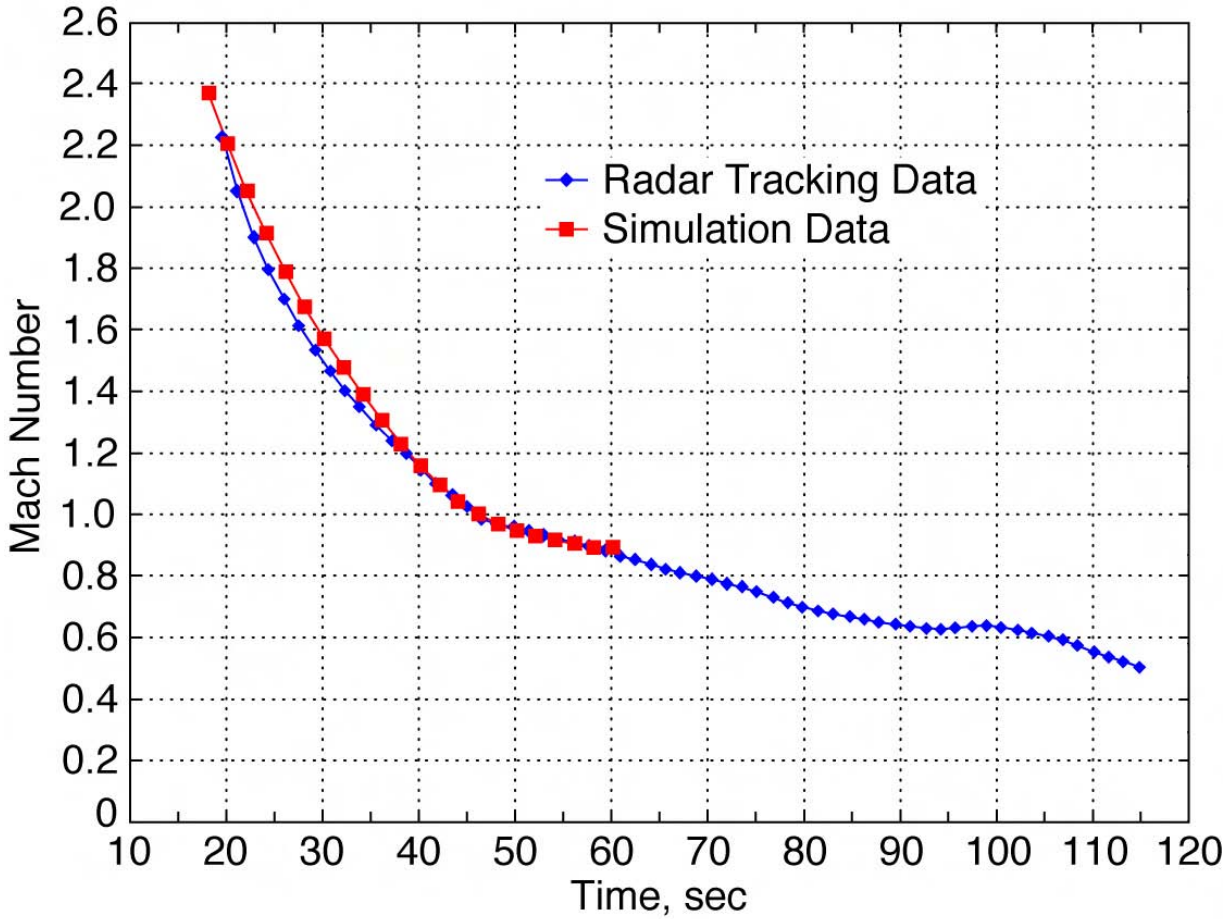
- Results from video analysis and use of trajectory simulation help corroborate capsule aerodynamics in supersonic regime (Mach 2.2 - 1.0)



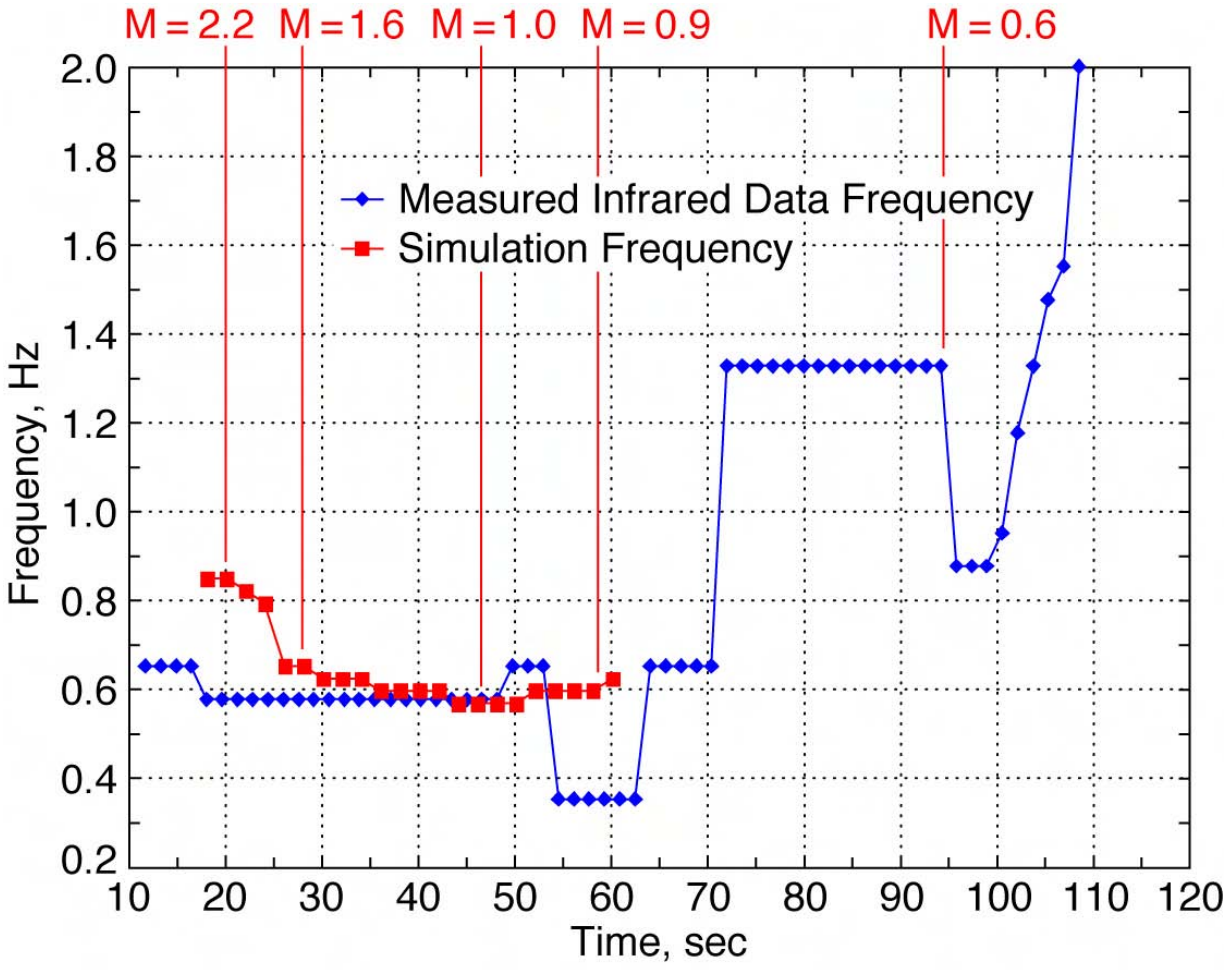
Capsule Deceleration Comparison (Supersonic Regime)

- Timelines of simulation and tracking data aligned at Mach 1
- Good agreement indicates aerodynamic database accurately captures capsule drag



Capsule Frequency Comparison (Supersonic Regime)

- Dominant frequency correlate well over range were data is available



Capsule Static Stability Assessment (Supersonic Regime)

- With confidence in oscillation frequency, an assessment of capsule static stability can be made since

  $$\text{Freq} \propto \text{dynamic pressure} * (\text{pitching moment slope})^{0.5}$$

- Appears to be good agreement between measured data and pre-entry predicted dynamics pressure variation
  - Assertion depends on agreement between predicted drag and measured drag and agreement of density profile
  - Accuracy of drag shown by comparison of deceleration profile
  - Balloon measured density profile shown to be within ±2.5% of pre-entry profile

- Consequently, agreement of frequencies indicates aerodynamics database reasonably predicted static stability

Hypersonic Capsule Attitude Assessment

- Since there was no onboard sensor data, capsule hypersonic attitude cannot be determined
  - Attitude must be inferred from observation of recovered heatshield
- There is very little, if any, charring of the shoulder region or aftbody of TPS
  - Inspection of forebody shows charring patterns that imply symmetry heating
  - Observations suggest that attitude must have been only a few degrees
    - Angle-of-attack is estimated to be no larger than 2.1° ± 1.4°
  - Pre-entry simulation predicted angle-of-attack of 1.38 ° with a maximum of 3°
- Overall observations support the assertion that the aero-dynamics database reasonably predicted hypersonic static stability

Capsule Shoulder and Aftbody Region

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Capsule Forebody Heatshield

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Phosphor Thermography Tunnel Tests

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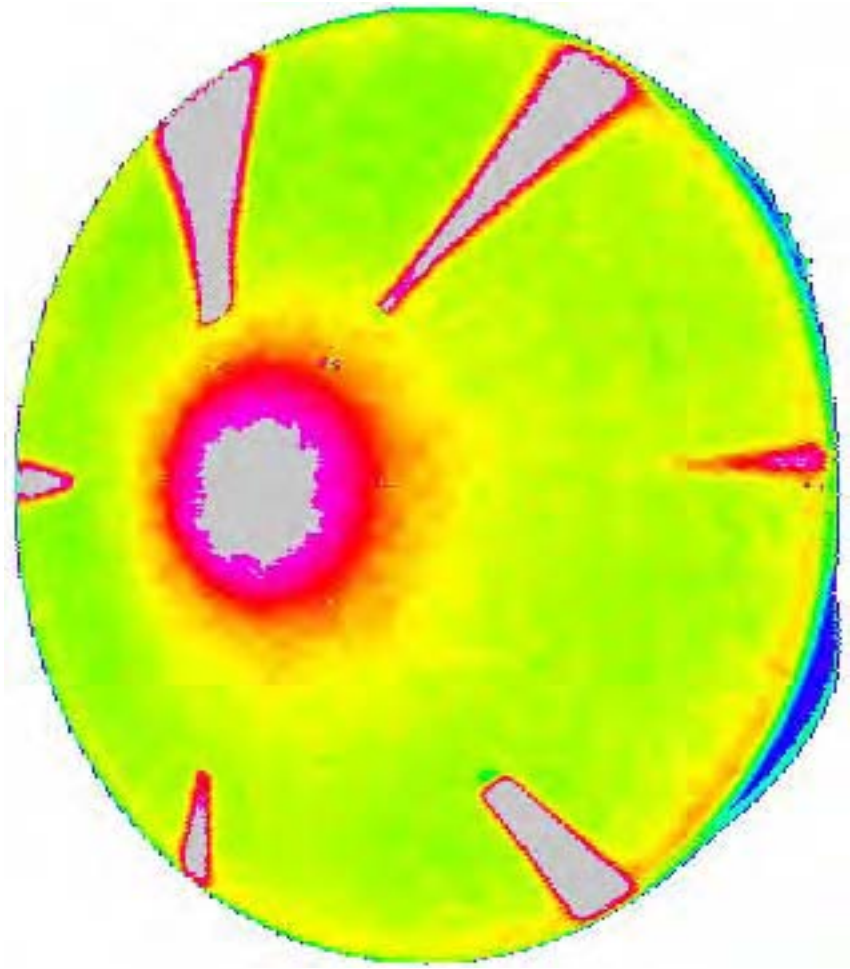

Trajectory Reconstruction

- Since there was no onboard sensor data, a “traditional” trajectory reconstruction could not be performed
  - Therefore, a Best Estimated Trajectory (BET) is calculated
- The BET is split into two phases: hypersonic and subsonic flight
- For hypersonic flight, only two data sources were available
  - Final Navigation entry state at atmospheric interface
  - Latitude and longitude data from UTTR radar tracking stations at the pre-entry predicted drogue deployment time
  - UTTR radar tracking stations acquired capsule from 34 km through impact
- With confidence in these two endpoints, a hypersonic trajectory is calculated using the pre-entry simulation

Trajectory Reconstruction (cont'd)

- Within the trajectory simulation, a multiplier on capsule drag was applied as the control parameter to determine the variation needed to patch the two endpoint conditions
  - An drag reduction of 8.1% is calculated
  - Altitude is within 380 m between simulation and tracking data

- The 8.1% reduction in drag can arise form multiple sources
  - Mis-prediction in entry state, capsule C_D, or atmospheric density
  - Final entry state was confirmed to be extremely accurate by STRATCOM
  - No measure of density available above 34 km
  - So, relative contributions between density and C_D cannot be determined

- However, an estimate for the hypersonic density can be approximated if an uncertainty in capsule C_D is assumed

Trajectory Reconstruction (cont'd)

- Typical C_D uncertainty in the hypersonic regime is ±4 (3-σ)
  - If a capsule C_D is assumed to be 1.5% low (a 1-σ occurrence), an estimate of atmospheric density above 34 km can be calculated
- With such an assumption, the atmospheric density encountered during the hypersonic flight can be approximated to be 6.6% lower than the pre-entry profile from GRAM
  - This estimate corresponds to 1.5-σ low profile from the GRAM variations
- Process for subsonic trajectory estimate is described in the paper

Genesis Best Estimated Trajectory

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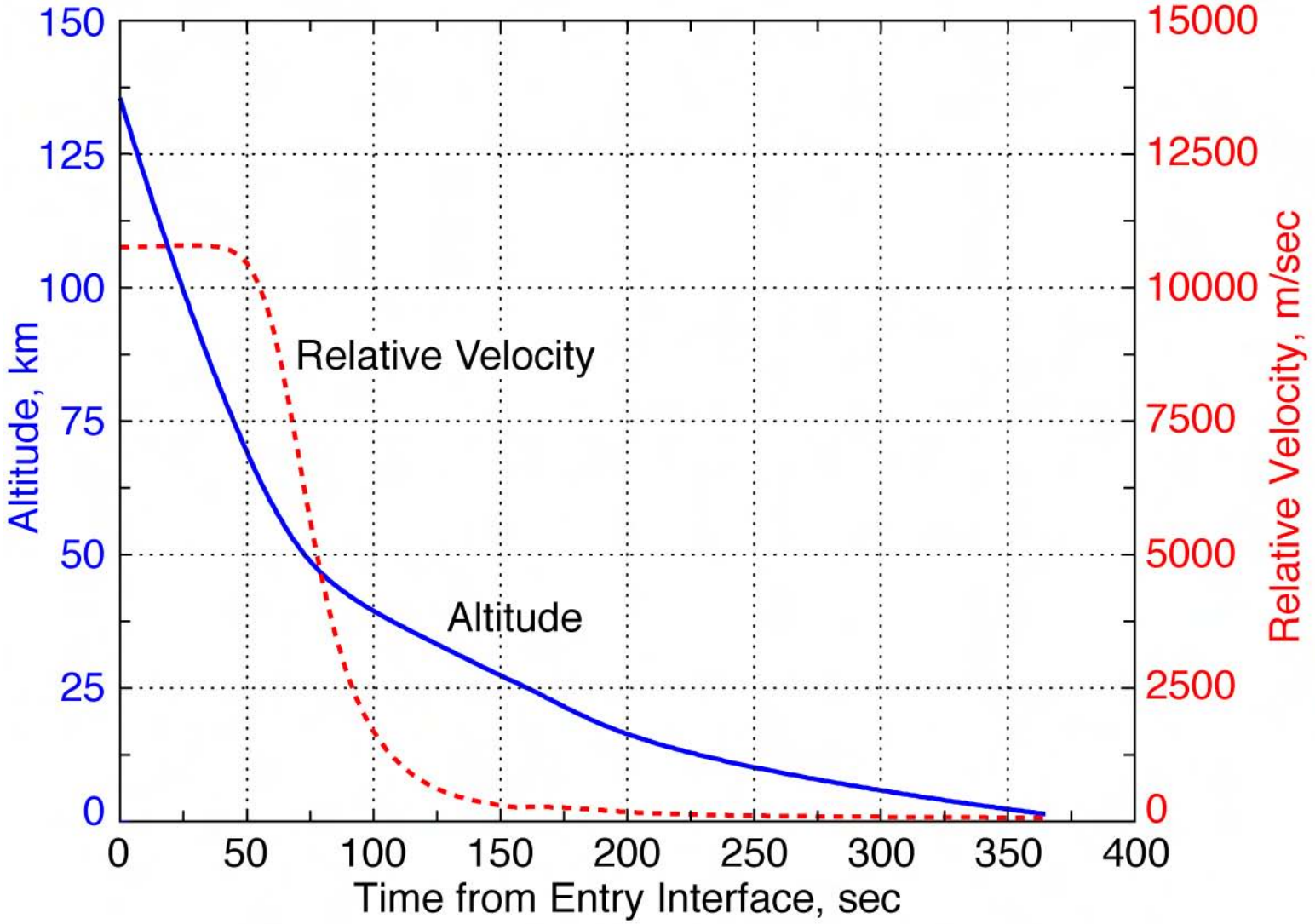

Summary

- An overview of the reconstruction analyses is described
- Atmosphere (density and winds) encountered during the entry were approximately 1-σ profiles
- Analysis on infrared video footage estimated the onset of capsule tumble at Mach 0.9
- Observations of the recovered heatshield indicated small attitude during hypersonic flight
- Overall assertion is that the Genesis entry flight performance was close to the nominal pre-entry predictions
- Consequently, the design principles and methodologies utilized for the flight dynamics, aerodynamics, and aerothermodynamics analyses were corroborated